Towards New Aortic Tissues Analogue Materials: Micro-mechanical Modelling and Experiments

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ABSTRACT

Human abdominal aortic tissue is a complex cylindrical soft sandwich structure, arranged in three different concentric layers. Within these layers, distribution and arrangement of all components display a double-helix architecture of wavy fibres, characterised by distinctive preferred orientations [1]. The macroscopic mechanical behaviour of human healthy abdominal aorta (AA) and aneurysmal (AAA) tissues is highly non-linear, anisotropic and essentially hyperelastic [2]. The global objective of this work is to design and process new artificial hyperelastic and anisotropic membranes mimicking the macroscopic histological and mechanical features of AA and AAA tissues. These materials will be then used to build more realistic phantoms of AAA for in vitro experiments [3]. The aim of the present study is (i) to develop a theoretical framework able to predict the optimal microstructure and mechanical behaviour of such AA/AAA analogues, and (ii) to provide experimental validation of micro-mechanical modelling.

Proposed target AA/AAA analogues are composite membranes composed of a thin and soft hyperelastic silicone layer reinforced by simplified periodic fibrous microstructures displaying preferred orientations. In an attempt to mimic main histological features of the biological tissues, three kinds of fibrous architecture were investigated: a *one-layer lattice* of *straight* fibres, a *one-layer lattice* of *wavy* fibres, and a *bi-layer lattice* of *straight* fibres. Each fibrous lattice can be seen as a repetition of a Representative Elementary Cell (REC) as sketched in Fig. 1(a) in case of the one-layer lattice. Fibres are supposed to be linked at the REC extremities A_1, A_2, A_3 and A_4. In between these points, the mechanical behaviour of the fibres are supposed to be of hyperelastic types. To fit bi-axial experimental data obtained from the literature [2], with normal or pathologic aortic tissues, the microstructure of the periodic lattices (fibre chord l_0, angle between fibres θ_0) together with the mechanical behaviour of the fibres (fibre tension-elongation curve) were optimised by using theoretical results arising from an upscaling process based on the homogenisation of periodic and discrete structures [4, 5]. From this theoretical work, it is shown that a material constituted by only one periodic lattice of fibres is clearly not sufficient to describe all the experimental data set. Instead, a quantitative agreement between measurements and the model predictions is obtained by using a material with two fibre lattices (see Fig. 1(b)). Besides, the microstructures and mechanical properties of the optimised fibrous lattices are strongly different for the abdominal healthy and aneurysmal arterial tissues. In particular, the optimal angles between fibres in the case of the healthy

aorta are consistent with histological data. Lastly, it must be pointed out that the anisotropic mechanical behaviour of the optimised material is described by only five parameters.

Based on these theoretical results, several types of commercial fibres were selected and their tensile mechanical behaviours were characterised. A specific device dedicated to the manufacturing of periodic fibrous lattices and square composite membranes was designed to control the architecture of the REC of the processed anisotropic hyperelastic membranes, *i.e.* the angle between fibres, and the fibre chord. The three kinds of fibrous microstructure were characterised by means of X-rays micro-tomograph, as illustrated on Fig. 1(a). The in-plane mechanical behaviour of the composite membranes was characterised under various loadings using a uniaxial tensile-testing device, and discussed with respect to above theoretical predictions.

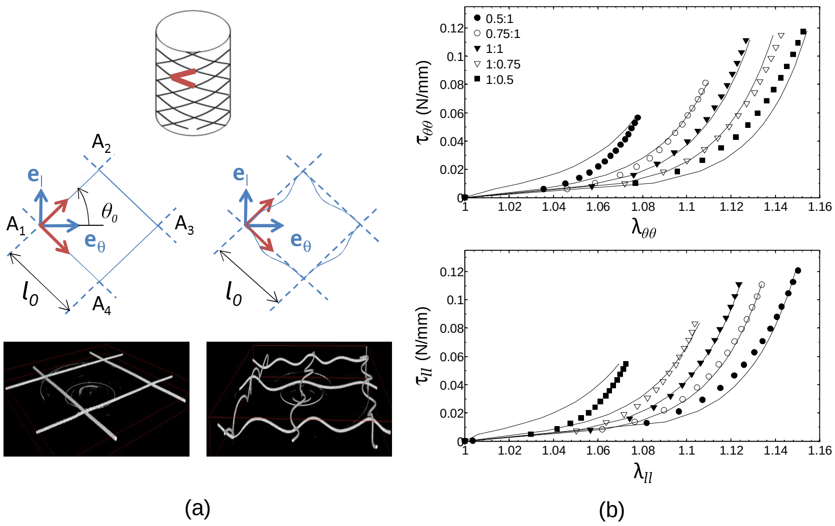

Figure 1: **(a)** Typical rhombic lattice under consideration and corresponding periodic REC of the *one-layer fibrous structure* solution in cases of straight fibres (left) and wavy fibres (right); **(b)** Comparison between the optimized theoretical predictions of the bi-layer model (solid lines) and Vande Geest experimental data from [2] (symbols) at the macroscopic scale for AA samples: Cauchy tension τ versus elongation. Legend refers to the controlled axial Piola-Kirchhoff tensions ratio.

References

[1] Holzapfel, G.A., Determination of material models for arterial walls from uniaxial extension tests and histological structure. *J. Theor. Biol.* 238:290-302, 2006.

[2] Vande Geest, J.P., Sacks, M.S. and Vorp, D.A., The effects of aneurysm on the biaxial mechanical behavior of human abdominal aorta. *J. Biomech.* 39:1324-34, 2006.

[3] Deplano, V., Knapp, Y., Bertrand, E. and Gaillard, E., Flow behaviour in an asymmetric compliant experimental model for abdominal aortic aneurysm. *J. Biomech.* 40:2406-13, 2007.

[4] Caillerie, D., Mourad, A. and Raoult, A., Discrete homogenization in graphene sheet modeling. *J. Elasticity* 84(1):33-68, 2006.

[5] Bailly, L., Geindreau, C., Orgas, L. and Deplano, V., Towards a biomimetism of abdominal healthy and aneurysmal arterial tissues. *J. Mech. Behav. Bio. Mater.* submitted, 2011.